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Active Cells for Multifunctional Structures

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Final Report

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14. ABSTRACT

This research effort explored the development of active engineered cells that exist as a self-contained electromechanical unit, with sensor/actuator, drive electronics, and battery embedded within a spherical elastomer housing. These building blocks will ultimately enable the creation of articulated structures in a straight-forward molding process: a large number of inexpensive, independently functioning sub-centimeter actuator units (‘cells’) are cast en masse as aggregate and joined via a flexible support matrix. Within a larger structure, each cell is autonomous and receives power and control signals wirelessly from distributed transmitters. Selective activation of clusters of cells through these transmitters produces the desired deformation of the structure. The absence of hardwired connections to each actuator unit streamlines fabrication significantly by allowing cells to be embedded as aggregate in resin or elastomer composites.

15. SUBJECT TERMS

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Final Technical Report
Period: June 1, 2011 – May 31, 2014 (end date)

I. Heading

PI Name: Aaron Dollar
Organization: Yale University
AFOSR Award Number: FA9550-11-1-0093
Award Title: Active Cells for Multifunctional Structures

II. Scientific and Technical Objectives

The proposed research effort explores the development of active engineered cells that exist as a self-contained electromechanical unit, with sensor/actuator, drive electronics, and battery embedded within a spherical elastomer housing. These building blocks will ultimately enable the creation of articulated structures in a straight-forward molding process: a large number of inexpensive, independently functioning sub-centimeter actuator units ('cells') are cast *en masse* as aggregate and joined via a flexible support matrix. Within a larger structure, each cell is autonomous and receives power and control signals wirelessly from distributed transmitters. Selective activation of clusters of cells through these transmitters produces the desired deformation of the structure. The absence of hardwired connections to each actuator unit streamlines fabrication significantly by allowing cells to be embedded as aggregate in resin or elastomer composites.

The research plan includes the following specific aims:

1) Explore subsystems that will enable self-contained active cells, including:
    a. Issues related to actuator choice and implementation
    b. Layout of the cell, including cell material and placement of components
    c. Development and evaluation of drive electronics
    d. Fabrication of the cell with embedded active components
2) Develop prototype active cells to evaluate their real-world feasibility and performance
3) Fabricate a proof-of-concept controllable structure consisting of a 6x6 array of actuator cells

These research efforts will enable a thorough feasibility evaluation of the proposed concept, and provided that results are promising, will help identify specific areas for in-depth future work.

III. Approach

We began this project by first investigating very simple contractile cells that can be attached to one another in order to produce large-scale redundant mechanical structures. While this was akin to a modular robotics approach, we wanted to ensure that we didn't encounter many of the pitfalls encountered by previous efforts in modular robotics, namely complexity of the robotic modules in both construction and function. To this end, we followed the biomimetic inspiration of mammalian muscle cells, where specialize cells that have a single function of providing a contractile force. This desire to have very simple active cells that were both contractile and load bearing required that we first address the issue of intercellular connectivity. Next, we focused on the design and construction of the active cells and built various structures and robotic platforms using the active cells to demonstrate versatility. Finally, we began to address issues of cell to cell

connectivity in lattice structure and the control algorithms necessary to achieve the ultimate objective of active structures through ensembles of contractile active cells.
The general approach has not deviated since the initial proposal, though we did have a new PhD student work on a related effort of conductive elastomer composites based on the cell-to-cell connectivity results of our early active cell research.

IV. Concise Accomplishments

(2012):

- Used rapid prototyping techniques to explore a variety of cell designs.
- Designed a simplified active cell using Nitinol as the actuation method and relying on Joule heating for contraction of the cell.
- Developed manufacturing techniques for reliably creating Nitinol spring coils in a variety of diameters and gauges.
- Developed simulations of random packing of active cells to determine connectivity as a function of surface area of conducting terminals. Also analyzed the effects of momentary disconnects in large structures of cells.

(2013):

- Continued improving cells designs of an ~16 *cm^3* active cells made of 3D printed endcaps, magnetic contacts between cells, and a single linear degree of freedom.
- Developed multiple robotic devices and structures using the first generation of cells, namely an inchworm robot, a rolling robot, and a parallel platform.
- Developed methods for optimizing the design of the active cells to maximum the stroked length of the active cells by tuning the stiffness of a passive spring in parallel with the Nitinol coils.
- Developed a conductive composite based on the packed cell-to-cell contact simulations developed in the previous year. This conductive composite relied on physical interactions of the copper aggregate in a polymer, rather than the chemistry of the aggregate and composite matrix materials.

(2014):

- Developed a second and third generation of cells that were almost two orders of magnitude smaller (~1 *cm^3*) with better cell-to-cell connectivity and higher recoverable strain.
- Characterized the newer cells in terms of their stress-strain behavior as a contractile unit.
- Worked further towards full autonomous functionality of a structure of cells by developing multi-physics simulations of the forward kinematics of a structure through minimization of the stored elastic energy in the structure with applied boundary conditions.
- Finalized development of cell optimization methods to include methods for optimization the stiffness variability of active cells and structures.

Publications: 5 peer-reviewed papers in journals and conferences.

V. Work Plan

While the award period is over and our funds have been spent, we are tying up a few loose ends. Our latest work on deformation and control of larger structures is being developed as one more conference and journal paper. Additionally, we are planning for future work related to the more general problem of creating event larger structure that follow the paradigm of simple cellular robotics modules that goes beyond contractile actuation to also include sensor cells and distributed, localize controller cells, for which we will likely be pursuing additional funds.

VI. Major Problems/Issues (if any)

(none)

VII. Technology Transfer

(none)

VII. Foreign Collaborations and Supported Foreign Nationals

Ashan Nawroj (Bangladesh) – PhD Student, Yale University
Paul E. I. Pounds, PhD (Australian) – Lecturer, University of Queensland

IX. Productivity

A. Refereed Journal Articles and Refereed Conference Papers

[J1] A. I. Nawroj, J. P. Swensen, and A. M. Dollar. Electrically conductive bulk composites through a contact-connected aggregate. PLoS ONE 8(12):e82260, 12 2013, http://dx.doi.org/10.1371%2Fjournal.pone.0082260.

[J2] J. P. Swensen and A. M. Dollar. The connectedness of packed circles and spheres with application to conductive cellular materials. PLoS ONE 7(12):e51695, 12 2012, http://dx.doi.org/10.1371%2Fjournal.pone.0051695.

[J3] J. P. Swensen, A. I. Nawroj, P. E. Pounds, and A. M. Dollar. Simple, scalable, active cells for articulated robot structures. Journal of Smart Materials and Structures, 2014 (in review).

[C1] J. P. Swensen, A. I. Nawroj, and A. M. Dollar. Simple, scalable, active cells for articulated robot structures. IEEE International Conference on Robotics and Automation (ICRA), 2014.

[C2] J. P. Swensen and A. M. Dollar. Optimization of parallel spring antagonists for nitinol shape memory alloy actuators. IEEE International Conference on Robotics and Automation (ICRA), 2014.

B. Non-Refereed Significant Publications

[A1] A. I. Nawroj, J. P. Swensen, and A. M. Dollar. Development of Active-Cells for Macroscopically Deformable Strcutures. To appear in Proc. ASME Conference on Smart Materials, Adaptive Structures, and Intelligent Systems (SMASIS), 2014.

[A2] J. P. Swensen and A. M. Dollar. Active-cells for the Construction of Redundant and Configurable Articulate Structures. Proc. ASME Conference on Smart Materials, Adaptive Structures, and Intelligent Systems (SMASIS), 2013.

[A3] A. I. Nawroj, J. P. Swensen, and A. M. Dollar. A Bulk Conductive Polymer Using Embedded Macroscopic Copper Cells. Proc. ASME Conference on Smart Materials, Adaptive Structures, and Intelligent Systems (SMASIS), 2013.

[A4] J. P. Swensen and A. M. Dollar. Towards hyper-redundant and super-configurable articulated structures. Proc. ASME Conference on Smart Materials, Adaptive Structures, and Intelligent System (SMASIS), pp. 3888–3895, 2012.

C. Books or Chapters

(none)

D. Technical Reports

(none)

E. Workshops and Conferences

(none)

F. Patents

(none)

G. Awards/Honors

- NASA Early Career Faculty Award 2014
- DARPA Young Faculty Award 2013

- Finalist for Student Hardware Competition, ASME Conference on Smart Materials, Adaptive Structures, and Intelligent Systems (SMASIS), 2014.
- John J. Lee Endowed Junior Faculty Chair, Yale University, Oct. 2012.
- First place in DARPA's Autonomous Robotic Manipulation-Hardware (ARM-H) Competition (partner with Harvard University and iRobot Corporation), June 2012.

X. Award Participants

PI:	Aaron Dollar (male non-minority)
Grad Students:	Ahsan Nawroj (male non-minority)
Postdocs:	John Swensen (male non-minority)
	Lael Odhner (male non-minority)
Undergraduate Students:	Andrew Black (male minority)
	Chinmay Jaju (male non-minority)